SLAC – PUB – 4667
June, 1988
(T/E)

SEARCH FOR AXION PRODUCTION IN $\Upsilon(1S)$ DECAYS*

KENNETH H. FAIRFIELD

Stanford Linear Accelerator Center
Stanford University, Stanford, California, 94309

Representing

The Crystal Ball Collaboration[a]

ABSTRACT

We present a search for axion production in radiative $\Upsilon(1S)$ decays using the Crystal Ball detector. We find no evidence for a signal and give a new upper limit, $\mathrm{Br}[\Upsilon(1S) \rightarrow a^0\gamma] < 4 \times 10^{-5}$, for $m_a < 2m_e$. Results from previous axion searches in both the Υ and J/ψ systems are discussed and compared to theoretical predictions.

Presented at the International Symposium on Production and Decay of Heavy Flavors, Stanford, California, September 1–5, 1987

⋆ Work supported by the Department of Energy, contract DE – AC03 – 76SF00515.

It has been more than a decade since Peccei and Quinn[1] first proposed their elegant solution to the problem of P and CP violation in the QCD Lagrangian with the introduction of a weakly coupled $U(1)_{PC}$ chiral symmetry. Shortly afterwards, Wilczek[2] and Weinberg[3] pointed out that the breaking of $U(1)_{PC}$ leads to a light, neutral, pseudoscalar boson—the axion. They proposed a number of possible decay channels in which to search for this new particle. One such channel is the decay of a heavy vector meson to an axion plus photon, $V \rightarrow a^{\circ}\gamma$. We present here a new search by the Crystal Ball for such axion production in $\Upsilon(1S)$ decays.

The mass of the axion is given by[3] $m_a \simeq 25N(x+\frac{1}{x})$ keV, which has a minimum of 150 keV at $x=1$ for three generations; x is the ratio of the vacuum expectation values of the two Higgs fields in the theory, $x \equiv \langle\phi_1\rangle/\langle\phi_2\rangle$. When $m_a < 2m_e$, the only decay available is $a^{\circ} \rightarrow \gamma\gamma$, which proceeds rather slowly: $\tau_{a\rightarrow\gamma\gamma} \simeq 7\times10^{-4}\ (\mathrm{MeV}/m_a)^5$ s. Given this long lifetime, a light axion will usually escape undetected from a relatively small detector, like the Crystal Ball.

The search for axions in Υ and J/ψ decays is attractive for two reasons. First, the coupling of the axion to quarks is proportional to the mass of the quarks, and, therefore, should be enhanced for these heavy vector mesons. Second, for *light* axions, the final state is very easy to detect and the signature rather striking: $V \rightarrow a^{\circ}\gamma$, where a° escapes undetected, leading to a single, high energy photon in the final state. The predicted decay widths are given by

$$\Gamma(\Upsilon \rightarrow a^{\circ}\gamma) = \frac{\Gamma(\Upsilon \rightarrow \mu^+\mu^-)}{8\sin^2\theta_W}\frac{M_{\Upsilon}^2}{M_W^2}\cdot C_{\Upsilon}\cdot\frac{1}{x^2}\quad, \tag{1}$$

$$\Gamma(J/\psi \rightarrow a^{\circ}\gamma) = \frac{\Gamma(J/\psi \rightarrow \mu^+\mu^-)}{8\sin^2\theta_W}\frac{M_{J/\psi}^2}{M_W^2}\cdot C_{J/\psi}\cdot x^2\quad. \tag{2}$$

Note that the Υ decay is proportional to $1/x^2$, whereas the J/ψ decay is proportional to x^2. This has led some authors[4] to suggest that taking the product of equations 1 and 2 would give an x-independent prediction. Recently, though, a number of authors have calculated radiative[5] and relativistic[6] corrections to the QCD predictions. To first order in α_s, the radiative corrections C in the above equations are large, $C \sim 0.5$, and they may have large errors due to higher order terms. Relativistic corrections may be of a similar size. Furthermore, the correction factors may not be the same for Υ and J/ψ; thus the product of equations 1 and 2 is subject large uncertainty, and we evaluate the two processes independently. Taking as an estimate[5] $C_\Upsilon = C_{J/\psi} = 0.5$, and using the measured values of the $\mu^+\mu^-$ decay widths,[7] the predicted branching ratios are,

$$\mathrm{Br}[\Upsilon(1S)\rightarrow a^o\gamma] = (9.7\pm0.6) \times 10^{-5} \cdot \frac{1}{x^2} , \tag{3}$$

$$\mathrm{Br}[J/\psi\rightarrow a^o\gamma] = (2.7\pm0.4) \times 10^{-5} \cdot x^2 \ . \tag{4}$$

Several groups[8–12] have previously searched for $V\rightarrow a^o\gamma$ with the a^o undetected. The most restrictive upper limits for $J/\psi\rightarrow a^o\gamma$ come from the Crystal Ball at SPEAR,[8] $\mathrm{Br}[J/\psi\rightarrow a^o\gamma] < 1.4\times10^{-5}$. Both Υ(1S) and Υ(3S) decays have been investigated: the CLEO[9] and CUSB[11] groups have published similar upper limits, $\mathrm{Br}[\Upsilon(1S)\rightarrow a^o\gamma] \lesssim 3\times10^{-4}$, while the CUSB group has produced the best limit in the upsilon family using Υ(3S) decays,[10] $\mathrm{Br}[\Upsilon(3S)\rightarrow a^o\gamma] < 1.2 \times 10^{-4}$. The J/ψ search excludes the region $x > 0.8$, whereas the Υ(3S) search constrains $x < 0.6$. With the present theory and level of corrections, we are still left with the possibility of a Peccei-Quinn axion provided $0.6 < x < 0.8$.

Recently, we have analysed data taken on the Υ(1S) resonance by the Crystal Ball at DORIS II. The Crystal Ball[13] is an ideal detector to search for the single-photon final state produced in $\Upsilon\rightarrow a^o\gamma$. It consists of a spherical array of 672 NaI(Tl) crystals covering 94% of the solid angle. In addition, endcap arrays of NaI(Tl) crystals extend the solid angle coverage to 98%. The measured energy resolution for electromagnetically showering particles is $\sigma_E/E = 2.7\%/\sqrt[4]{E\ (\mathrm{GeV})}$, while angular resolution varies from 1° to 2° depending on the deposited energy. A tracking chamber of four cylindrical layers of proportional tubes separates charged and neutral particles.

We look for candidate events having a single energetic photon in the detector, and nothing else. The data sample consists of 44 pb^{-1} corresponding to 460,000 $\Upsilon(1S)$ decays. Selected events must have been triggered by the "total energy" trigger, which has a threshold of 1.8 GeV deposited energy in the main Ball, and is 100% efficient above 2.0 GeV. There must be exactly one neutral track in the event with 1.8 GeV $< E_\gamma < E_{Beam}(1 + 3\sigma_E)$, and no charged tracks. The upper energy limit rejects interacting cosmic rays that may deposit considerably more than the beam-energy in the Ball. There may be no other neutral tracks in the event having $E_\gamma > 100$ MeV, nor may there be more than 30 MeV energy deposited in the endcap crystals, or in the crystals that border the opening for the beam pipe in the main Ball. The high-energy photon must satisfy fiducial requirements which reduce background from $e^+e^- \to \gamma\gamma$, in which one of the photons is lost through the crack between the upper and lower hemispheres of the Ball, *etc.* Finally, the pattern of energy deposition in the connected region that defines the candidate photon, that is, the set of all contiguous crystals with at least 10 MeV deposited energy, must pass a set of tight cuts designed to assure that the energy cluster is consistent with being produced by a single photon, and not by a neutral hadron or a pair of photons from a π^0 decay, *etc.* The detection efficiency was determined in part from real $e^+e^- \to e^+e^-(\gamma)$ and $e^+e^- \to \gamma\gamma(\gamma)$ events and in part from a detailed Monte Carlo simulation of the detector. The overall detection efficiency for single photons with $E_\gamma > 2.0$ GeV was determined to be 0.34.

The above criteria select a total of 37 single-photon events with $E_\gamma >$ 2.0 GeV, whose energy distribution is shown in Fig. 1a. There is an evident peaking of events with E_γ near the beam energy, which is exactly the signature expected for a light axion. In order to estimate the background, we have also applied the above analysis to 93.3 pb^{-1} of data taken on the $\Upsilon(4S)$ resonance, which decays 100% to $B\overline{B}$ pairs. The results are shown in Fig. 1b where the

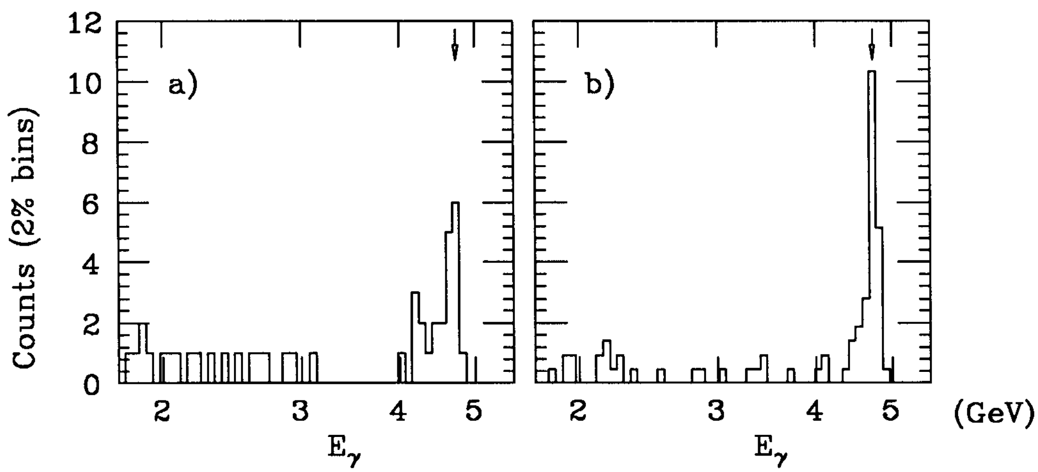

Fig. 1 Distribution of photon energy, E_γ, for (a) $\Upsilon(1S)$ data, and (b) $\Upsilon(4S)$ data. Arrows indicate the beam energy in the two data sets.

number of $\Upsilon(4S)$ events has been scaled by the ratio of luminosities for the two data sets and where the photon energy of the $\Upsilon(4S)$ data has been scaled by the ratio of beam energies to the $\Upsilon(1S)$ energy. The $\Upsilon(4S)$ data exhibit the same peaking of events near the beam energy as is seen in the $\Upsilon(1S)$ data, from which we conclude that these events are due to assorted background processes including beam-gas interactions and QED interactions. Using the $\Upsilon(4S)$ data as an estimate of the nonaxion background, we do a bin-by-bin subtraction. The resulting subtracted spectrum is shown in Fig. 2, along with the 90% C.L. upper limit assuming a monoenergetic photon, and including the effect of detector resolution.

As can be seen from the figure, the upper limit never exceeds 4×10^{-5}. From Eq. (3), this constrains $x < 1.5$. Taken together with the earlier Crystal Ball analysis of J/ψ decays, which required $x > 0.8$, we can exclude the standard Peccei-Quinn axion by about a factor of two. because there may be further reductions in the theoretical predictions as higher-order corrections are calculated, we give in Fig. 3 the excluded regions of x versus the correction factor, C, in the branching ratio formulas, equations 1 and 2. Note that the upper limits from $V \rightarrow a^0\gamma$

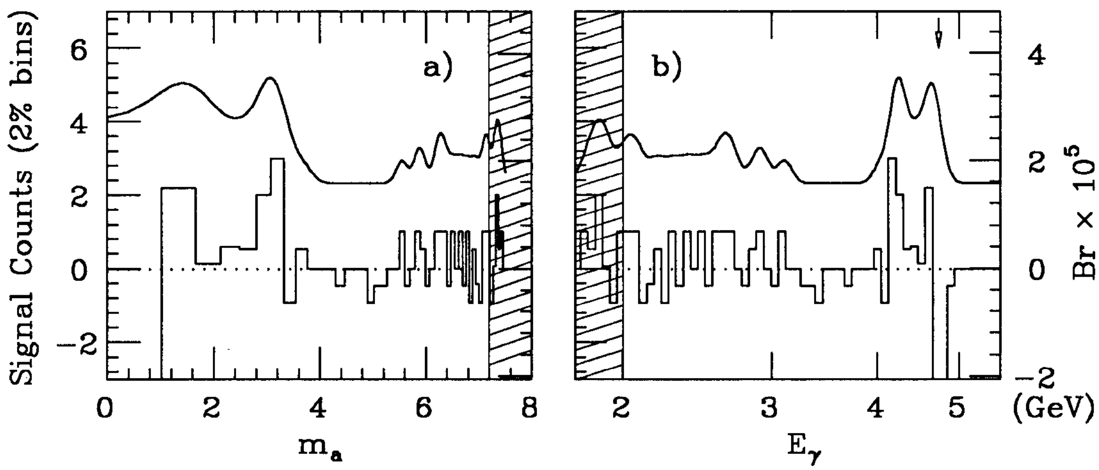

Fig. 2 Histogram of the background-subtracted event distribution as a function of (a) the mass recoiling against the photon, m_a, and (b) the photon energy, E_γ (left scale in both figures). The solid curve gives the 90% C.L. upper limit for $\Upsilon(1S) \to a^0\gamma$ (right scale in both figures). Arrow in part (b) indicates the beam energy.

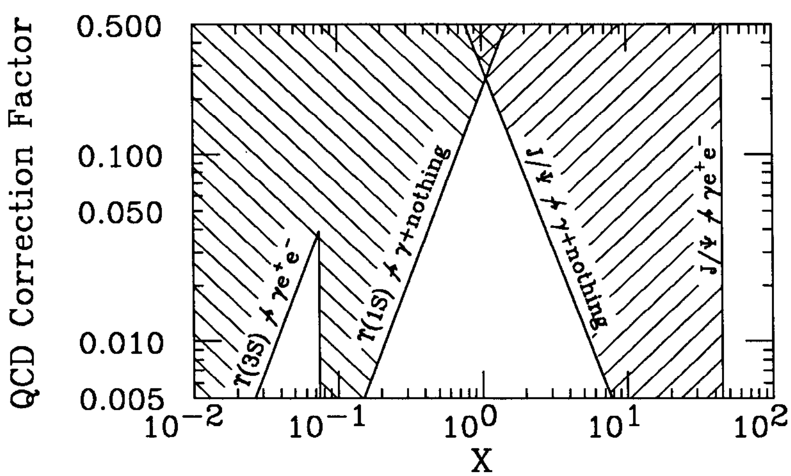

Fig. 3 The excluded regions of the parameter, x, as a function of the QCD correction factor, C. We include limits for $\Upsilon(1S) \to \gamma + nothing$ from this experiment, for $J/\psi \to \gamma + nothing$ from reference 8, and for $\Upsilon(1S) \to \gamma e^+e^-$ from reference 11. For $J/\psi \to \gamma e^+e^-$, see text. (Figure after Buchmüller and Cooper, reference 14.)

become much weaker for values of $x > 13.5$ or $x < 0.074$ because the decay $a^0 \to e^+e^-$ dominates in this case. However, the nonobservation of $V \to a^0\gamma \to e^+e^-\gamma$ in $\Upsilon(1S)$[11] decays extends the excluded region to $x \gtrsim 0.002$, whereas corrections for the reduced branching ratio for $a^0 \to \gamma\gamma$ relative to $a^0 \to e^+e^-$ in J/ψ decays[14] can extend the excluded region out to $x < 45$.

Our upper limit is valid for any two-body $\Upsilon(1S)$ decay into γ plus a noninteracting long-lived exotic, for $M_{\text{exotic}} < 7.2$ GeV. By modeling the whole photon energy range, we also can exclude radiative decays to multiple noninteracting exotics, $\text{Br}[\Upsilon(1S) \to \gamma + \text{N-exotics}] < 9.8 \times 10^{-5}$. The present analysis is unable to search for such exotic final states with a recoil mass greater than 7.2 GeV due to increased QED backgrounds. However, in a separate analysis,[15] we have used the decay chain, $\Upsilon(2S) \to \Upsilon(1S)\pi^0\pi^0 \to X + \gamma\pi^0\pi^0$, which is very clean and free of QED backgrounds. While the results are severely limited by small statistics, they have allowed the investigation of single-photon final states with energies 500 MeV $< E_\gamma <$ 2.0 GeV, or, equivalently, a recoil mass of $8.9 > M_X > 7.2$ GeV. The upper limit from this analysis is $\text{Br}[\Upsilon(1S) \to \gamma + X] < 0.011$ to 0.0023 for the mass range given.

In conclusion, we have searched for decays, $\Upsilon(1S) \to a^0\gamma$, and have found no significant signal above background. We have determined a new upper limit, $\text{Br}[\Upsilon(1S) \to \text{a}^0\gamma] < 4 \times 10^{-5}$ (90% C.L.), for $m_a < 2m_e$. Moreover, taken together with the previous Crystal Ball limit for J/ψ decays, this rules out the simplest axion model (but including first-order QCD radiative corrections) by a factor of two, over three orders of magnitude in the parameter, x.

[a] The Crystal Ball Collaboration includes:
California Institute of Technology, Pasadena, CA 91125; Carnegie-Mellon University, Pittsburgh, PA 15213; Cracow Institute of Nuclear Physics, Cracow, Poland; Deutsches Elektronen Synchrotron DESY, Hamburg, Germany; Universität Erlangen-Nürnberg, Erlangen, Germany; INFN and University of Firenze, Italy; Universität Hamburg, I. Institut für Experimentalphysik, Hamburg, Germany; Harvard University, Cambridge, MA 02138; University of Nijmegen and

NIKHEF-Nijmegen, The Netherlands; Princeton University, Princeton, NJ 08544; Department of Physics, HEPL, and Stanford Linear Accelerator Center Stanford University, Stanford, CA 94309; Universität Würzburg, Würzburg, Germany;

References

1. Peccei, R.D. and Helen R. Quinn. Phys. Rev. Lett. **38**, 1440 (1977).
2. Wilczek, F. Phys. Rev. Lett. **39**, 1304 (1977). Wilczek, F. Phys. Rev. Lett. **40**, 279 (1978).
3. Weinberg, Steven. Phys. Rev. Lett. **40**, 223 (1978).
4. Porter, F.C. and K.C. Königsmann. Phys. Rev. **D25**, 1993 (1982).
5. Nason, P. Phys. Lett. **175B**, 223 (1986).
6. Aznauryan, I.G., S.G. Grigoryan, S.G. Matinyan. 1987. Yerevan Physics Institute preprint EFI-967-17-87. Aznauryan, I.G., S.G. Grigoryan, S.G. Matinyan. Pis'ma Zh. Eksp. Teor. Fiz. **43**(11), 449 (1986).
7. Particle Data Group. Review of Particle Properties. Phys. Lett. **170B** (1986).
8. Edwards, C., *et al.* (Crystal Ball – SPEAR) Phys. Rev. Lett. **48**, 908 (1982).
9. Alam, M.S., *et al.* (CLEO) Phys. Rev. **D27**, 1665 (1983).
10. Sivertz, M., *et al.* (CUSB) Phys. Rev. **D26**, 717 (1982).
11. Albrecht, H., *et al.* (ARGUS) Phys. Lett. **179**, 403 (1986).
12. Niczyporuk, B., *et al.* (LENA) Z. Phys. **C17**, 197 (1983). Franzini, P., *et al.* (CUSB) Phys. Rev. Lett. **56**, 2672 (1986). Bowcock, T., *et al.* (CLEO) Phys. Rev. Lett. **56**, 2676 (1986).
13. Bloom, E.D. and C.W. Peck. Ann. Rev. Nucl. Part. Sci. **33**, 143 (1983); Oreglia, M., *et al.* Phys. Rev. bf D25, 2259 (1982).
14. Buchmüller, W. and S. Cooper. MIT preprint MIT-LNS-159 (1987).
15. Lefler, J.S. Ph.D. Thesis, Stanford University. SLAC-Report-293 (1986).